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Extremely Uniform Electrodeposition of Submicron Schottky Contacts,

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A plating technique has been developed that yields extremely uniform metal deposits on semiconductor surfaces. This technique utilizes high field pulses that are extremely short in duration. The technique has produced theoretical Schottky barrier diode spreading resistances for contacts with dimensions ranging from 2.0 to 0.12 µm in diameter.

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PREFACE

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EXTREMELY UNIFORM ELECTRODEPOSITION OF SUBMICRON SCHOTTKY CONTRACTS

An electroplating technique, high-field pulse-plating (HFPP), has been developed for obtaining uniform coverage of metals deposited on semiconductor surfaces. The technique solves a problem which has plagued the fabrication of millimeter- and submillimeter-wavelength Schottky barrier diodes as the diameters of these devices have been reduced to micron and submicron dimensions.[1-3] Ideal performance of Schottky barrier diodes is only achievable if the deposited metal electrode is uniformly in intimate contact to the semiconductor surface on a scale which is small compared to the dimensions of the device. We report near ideal deposition of plated contacts to n-type GaAs for diameters as small as 1200 Å.

The implications of this achievement are considerable. The performane of high-frequency low-noise receivers depends critically on Schottky barrier type devices. The electrical behavior of the Schottky diodes fabricated by this technique implies important improvements in receiver performance at mm and far infrared wavelengths, a region of interest for applications in communications, radio astronomy, and precision frequency metrology experiments. This development is also necessary for the successful fabrication of more complex structures such as the contact array diode,[4] a structure applicable to both conventional Schottky barrier type devices as well as the super-Schottky diode.[4,5]

The all-important parasitic power losses of a Schottky barrier mixer or varactor diode are consumed in the series resistance of the device, and as such, a reduction in this resistance results in a direct improvement in device performance. In a well designed Schottky diode where surface and back contact impedances are minimized, the series resistance is dominated by the spreading resistance R_s of the device, the resistance due to the constriction of the current flow in the semiconductor at the contact. The theoretical value of the spreading resistance R_s for a contact to a uniformly (nonepitaxial) doped semiconductor is given by[6]

$$R_s = \rho/2d \qquad (1)$$

where ρ is the resistivity of the semiconductor and d is the diameter of the contact. Values of R_s are typically larger than indicted by Eq. (1) because of poor coverage of the deposited metal. For 0.5-μm diameters, a discrepancy factor of the order of 3 is observed,[2,3] and this factor increases as the diameter is reduced.

The HFPP technique represents a very different approach to the electrodeposition of metals. Presently used plating methods rely on relatively low rates of deposition which are controlled by metal ion diffusion mechanisms within the bath. HFPP utilizes an extremely fast deposition rate which is controlled by the electric field in the bath very close to the deposition surface. Deposition rates are 10^4-10^5 times faster than with conventional electroplating (or vapor deposition) methods. The technique requires pulses of current and voltage which are fast rising, large, and nearly constant in magnitude, and very short (a few hundred nsec for Pt solutions). The pulses must also have a low duty cycle to allow time ($\approx$ 1 msec) for the solution to relax to a uniform concentration of metal ions near the plated area. The technique closest experimentally to HFPP is a pulse-plating technique described by Burrus.[7] His technique is based on relatively long pulses of current and voltage (e.g., RC discharges), and as such, the plating is a hybrid combination of pulse and dc plating.

The success of HFPP depends critically upon this high rate of deposition. Uniform coverage is achieved when the condensed metal crystals on the semiconductor are densely packed, a situation that results if the condensed metal crystals can be forced to nucleate on the semiconductor in a random nonpreferential manner, rather than on fvored sites such as on existing plated crystallites. Such a nonpreferential process is spontaneous nucleation and has as a key requirement for its occurrence that the number of atoms at a potential condensation site exceed a certain critical number.[8] Condensed crystals with less than this number are not stable. Consequently, with extremely high deposition rates spontaneous nucleation can dominate the condensation, and uniform coverage is the end result. This type of plating is to be contrasted with dc plating where initial condensation occurs preferentially on sites more favorable to nucleation, and these sites serve to getter subsequent metal atoms and grow at the expense of new nucleation centers being created. Fewer nucleation centers (fewer crystals) result in less overall intimate contact between the deposited metal and the semiconductor surface.

This spontaneous nucleation requirement and the kinetics within the plating bath establish constraints on the width of an applied pulse. Conditions within the solution during an applied pulse are sketched in Fig. 1. A high electric field E is impressed across a region of depleted metal ions of width ℓ. This depletion width increases with time and, as a result, the field E and, hence, the rate of deposition, decrease with time. Since the process requires a high rate of deposition throughout the entire pulse, the pulse must be terminated at the subcritical deposition point. This subcritical point establishes a maximum pulse width for a given pulse voltage. A minimum width also exists for the pulse, since spontaneous nucleation requires enough metal be delivered per pulse.

Successful Pt depositions have been obtained using rectangular pulses 25-35 V in height, 200-nsec long, and a repetition rate of 1000 pulses/sec. Deposition rates of 10^5Å/sec ($J \approx 2 \times 10^5$A/cm^2 with ℓ_{max} the order of 1000 Å are commonly experienced. The use of longer pulses or higher duty rates yields coverage with noticeably larger grain size. At the other extreme, plating appears not to proceed at all for pulses less than 50 nsec in width. The Pt plating solution is a commercially produced chloride-based acid solution.[9] Care must be taken during the preplate HCl (concentrated) etch (5 min) and during the plating operation that the surface is constantly being flushed with fresh solution. This procedure avoids the formation of H_2 gas bubbles; bubble formation markedly reduces the uniformity of the plated diodes. The 10-A capability of the pulse generator was sufficient to Pt plate areas as large as 4×10^{-4} cm^2 with extremely uniform coverage. The HFPP process is independent of the size and shape of the anode electrode, because the effective counter electrode for the process is the depletion edge of the solution shown in Fig. 1. A systematic study of the voltage requirements has not been made. However, as a general rule, large areas require larger applied voltages due to the area dependency of the resistive potential drop in the "spreading

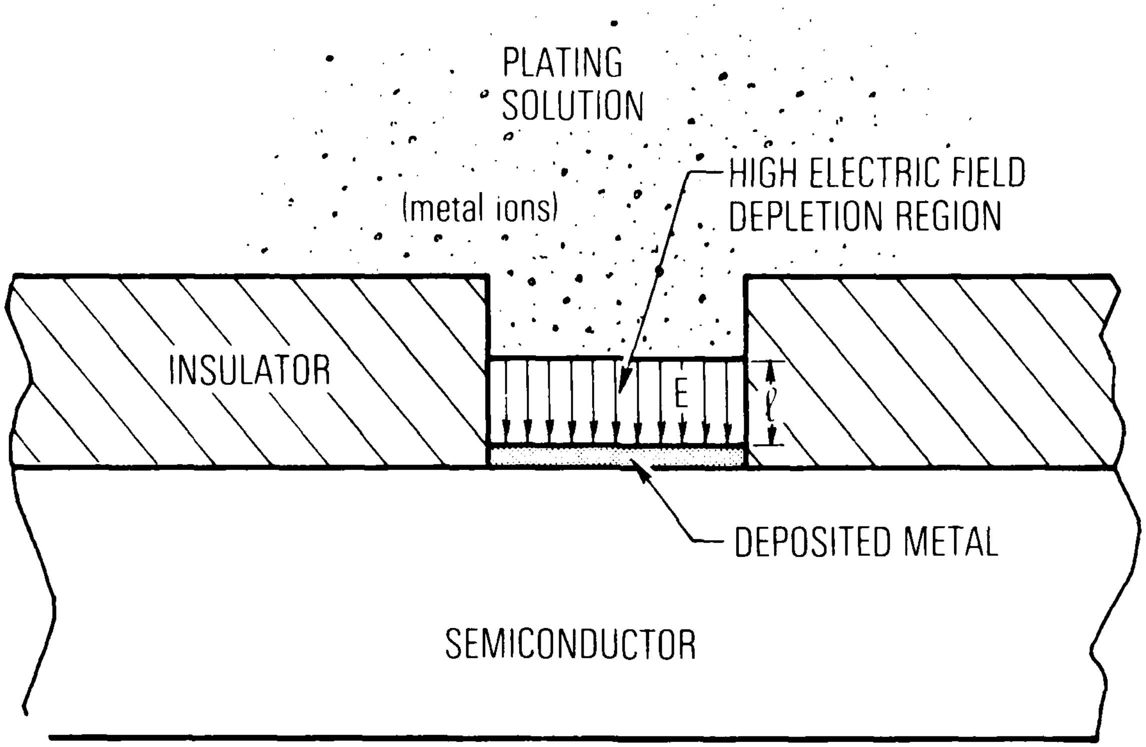

Fig. 1. A sketch of the bath conditions with high-field pulse-plating.

resistance" region of the solution. All depositions have been done at room temperature without special controls on the temperature of the bath.

A comparison of the coverage with dc plating and HFPP is shown in Fig. 2 for similar total amounts of deposited Pt metal. Examination of the HFPP sample indicates crystalline structure of less than 200 Å, the resolution ca pablity of the scanning electron microscope (SEM). Figure 3 illustrates the improvement in uniformity of Schottky diodes using this technique. The results shown are typical for $d \approx 0.5$ μm.

The measured series resistances obtained from Pt/n-GaAs Schottky barrier diodes fabricated using this technique are shown in Fig. 4. A moderately low doping of 4×10^{17} cm^{-3} was chosen for the n-GaAs to ensure that the series resistances would be sufficiently large and, hence, easily measured. The spread in the R_s values shown represents the range of values obtained from the measurement of approximately 10 different diodes in an array of identically produced contracts. After the electrical measurements were taken, the insulating layer was stripped away allowing the base diameters to be measured directly using an SEM. The uncertainty in the diameter measurements is approximately ± 5%, as shown. No adjustable parameters are involved in establishing the theoretical line shown in Fig. 4; it has been drawn using Eq. (1) and an independently measured value of ρ obtained from a four-point probe measurement. As shown, both the agreement between theory and experiment and the small deviations from diode to diode are quite exceptional. The contact array diode requires diameters as small as 1200 Å for efficient high-frequency detection. These data ensure its success.

Results similar to Fig. 4 have been obtained using plated contacts of Pb, a desirable metal for super-Schottky diodes.[4,5] With this metal, longer pulses (≈ 1 μsec) are acceptable, because the density of the plating solution is greater. Denser plating solutions result in smaller metal ion depletion regions and, hence, larger electric fields at the deposition face for any instant of time. As a result pulse widths can be longer. Deposition rates of 10^6 Å/sec for Pb are commonly obtained.

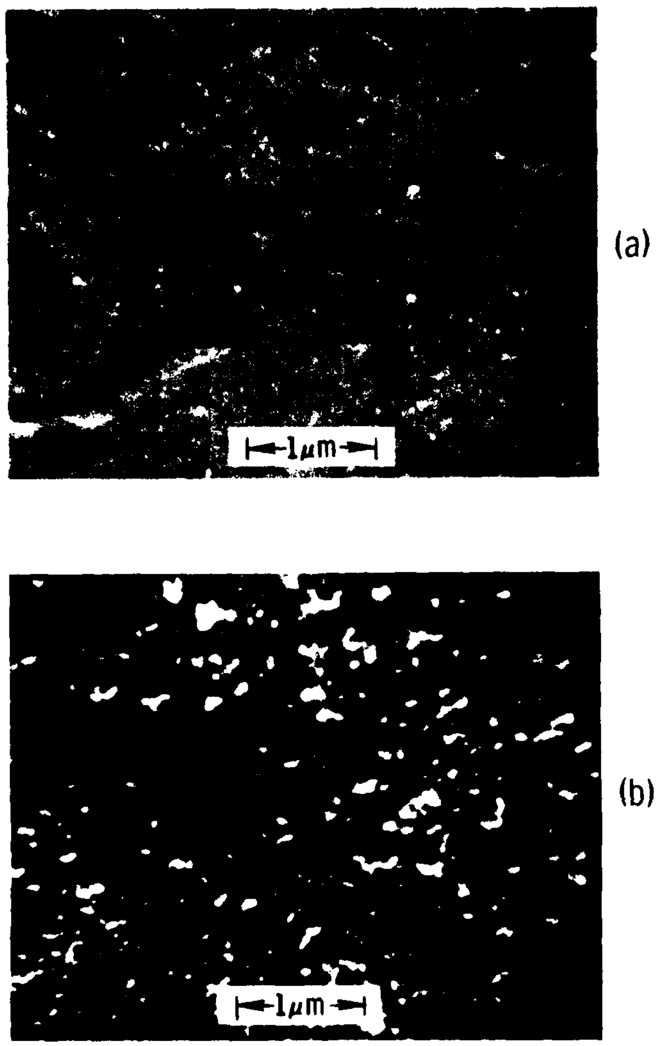

Fig. 2. A comparison of the coverages obtained with high-field pulse-plating and dc plating methods. The light areas are plated Pt; the dark areas are the base GaAs surface. (a) High-field pulse-plating of Pt. (b) DC plating of Pt.

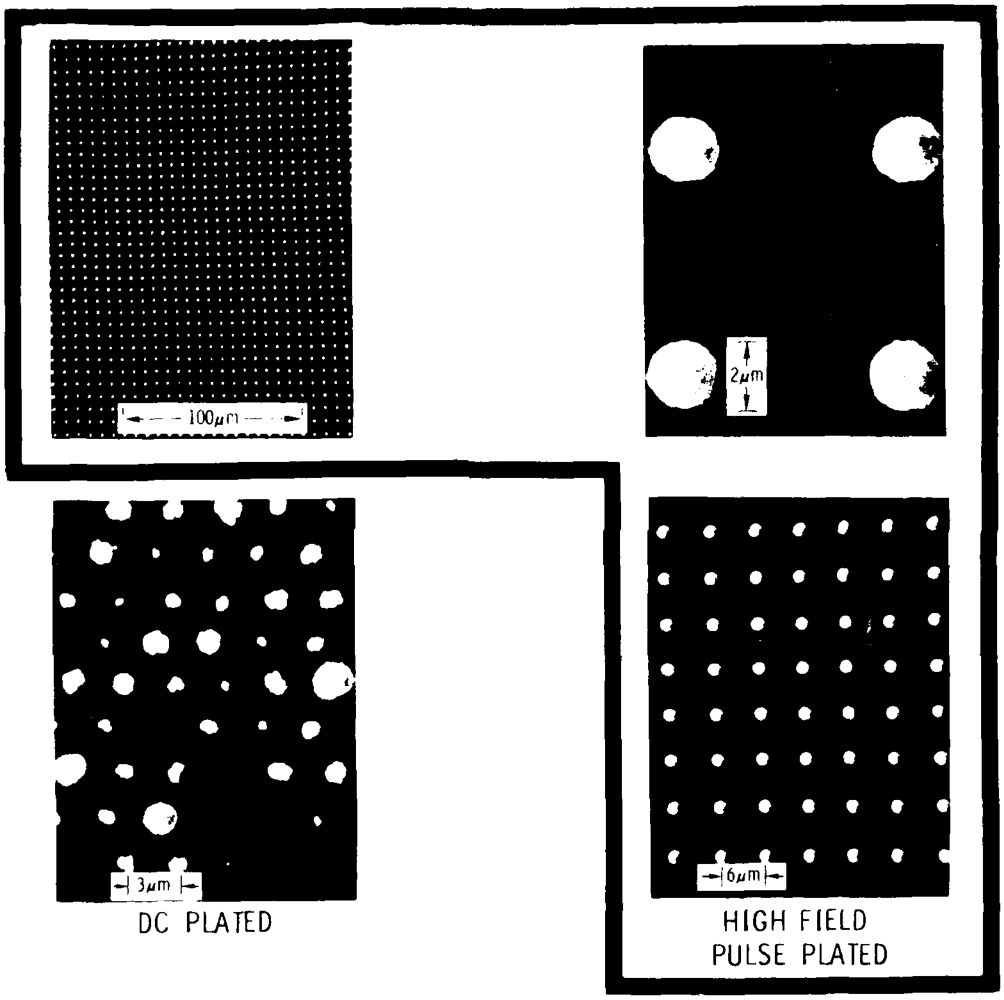

Fig. 3. A comparison in the uniformity of the plated diodes. The diodes are plated through electrolithographically produced windows in the insulator and consist of a thin Pt plate followed by a heavily plated mushroom-shaped Au overplate. The base diameters of the diodes are 0.5 μm.

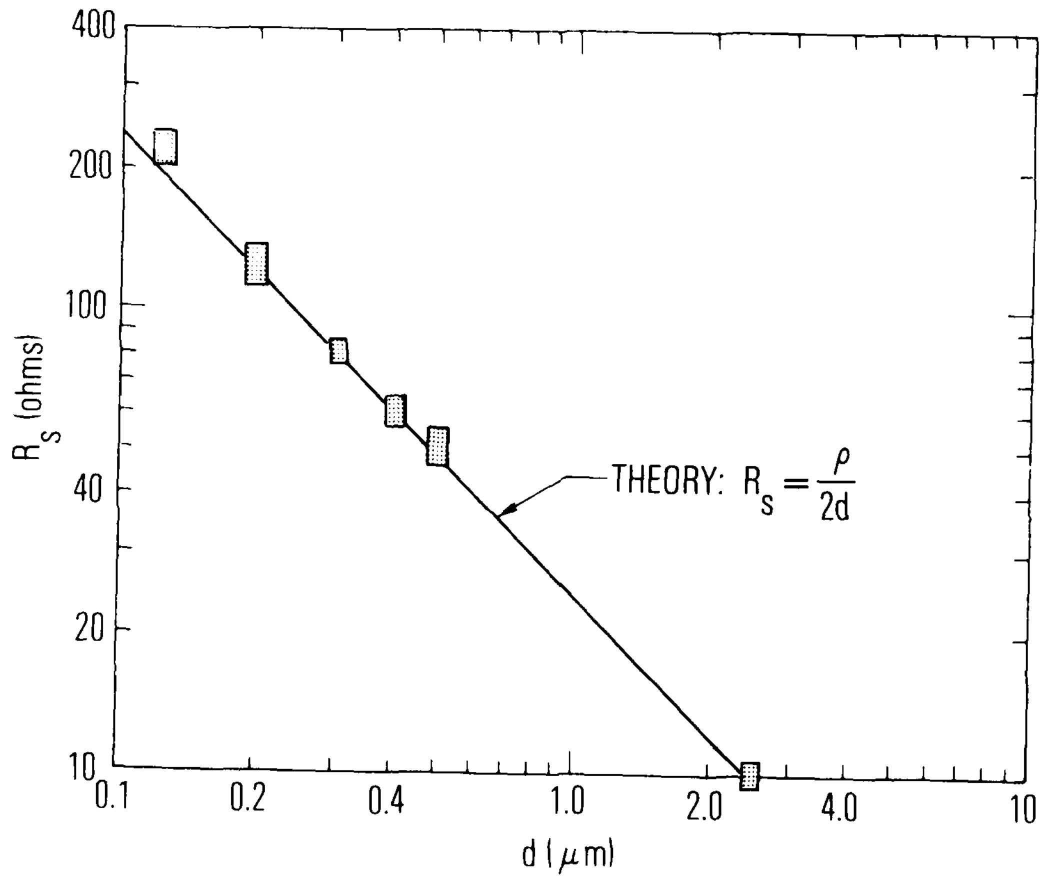

Fig. 4. Measured series resistance of pulse-plated Au/Pt/n-GaAs diodes as a function of contact diameter. The theoretical line is obtained using a value of the bulk resistivity $\rho = 4.8 \times 10^{-3}$ ohm cm obtained from an independent set of four-point probe measurements; it is not a fitted curve.

Figure 5 shows the I-V characteristic of a HFPP 0.25- μm Pt contact on 4×10^{17} cm^{-3} n-GaAs. The exponential region of this characteristic yields a barrier height of 0.90 eV and an ideality factor n of 1.24. Barrier heights are typically within ± 0.02 eV over a 128 x 128 array of contacts. The linear high-current region of the I-V characteristic shown in the inset of Fig. 5 yields a value for R_s of 90 ohms. With respect to leakage currents, this characteristic is typical of the diodes measured; leakage currents are negligible down to 10^{-10} A, the limit of our instrumentation.

These submicron Schottky diodes have yielded excellent performance as mixers and detectors at submillimeter wavelengths, primarily because of their small junction capacitance.[10] Tested in an open mount, HFPP 0.25-μm diodes have demonstrated a heterodyne minimum detectable power of 5×10^{-17} W/Hz and a video noise-equivalent power (NEP) of 2×10^{-9} $W/Hz^{1/2}$ at a wavelength of 119 μm. Noise measurements on these diodes yield a 1/f noise corner frequency of 50 MHz.

The properties of these deposited films may be useful for other types of electronic devices. Specifically, these films should be denser and, hence, more conductive.[11] The conductivity of metal films is a critical parameter in a variety of high-frequency devices. For instance, with GaAsFET devices, the resistance of the gate electrode is an important limiting resistive parameter at high frequencies.

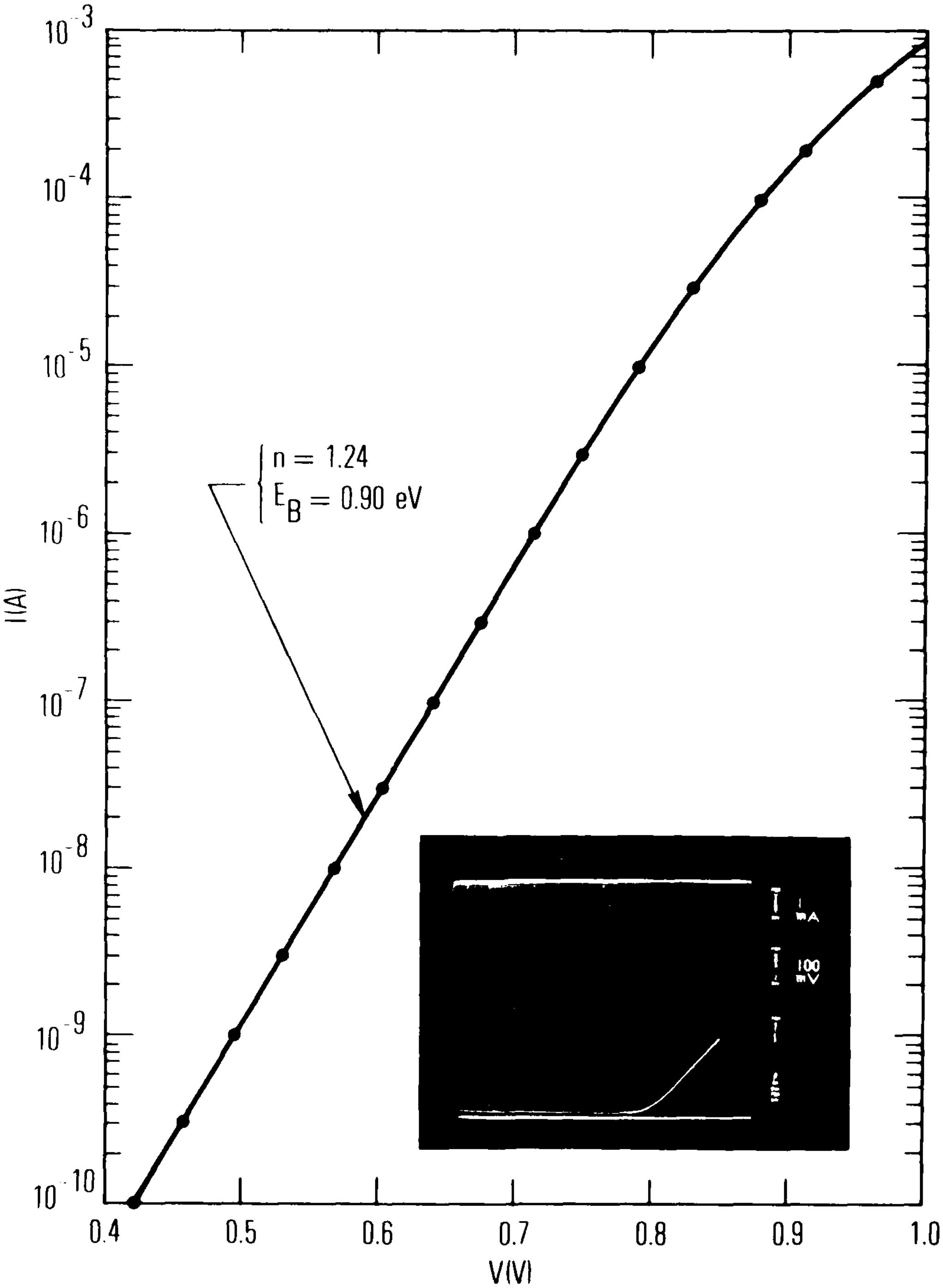

Fig. 5. The I-V characteristic of a high-field pulse-plated 0.25-μm Pt contact on 4×10^{17} n-type GaAs at room temperature. The origin of the linear display of the characteristic shown in the inset has been displaced to the left to allow a direct measurement of the series resistance R_s.

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